Lifetime of Electrolytic Capacitors in SINAMICS PERFECT HARMONY GH180 Air-cooled Drives

Objective

The purpose of this paper is to provide technical information with regards the lifetime of the electrolytic capacitors used in the SINAMICS PERFECT HARMONY GH180 powers cells.

This paper provide a basic overview of electrolytic capacitors, the factors associated with the lifetime of the capacitors used in the SINAMICS PERFECT HARMONY GH180 power cells, and the important differentiation between the design life of a cell and the real service life of a cell in different customer installation and operating situations.

The data shown in this paper is applicable to all SINAMICS PERFECT HARMONY GH180 air-cooled drives, manufactured in New Kensington, Pennsylvania.

Basics of Aluminum Electrolytic Capacitors

Introduction

Aluminum electrolytic capacitors are widely used in various switched mode power converters as DC-link capacitors for smoothing and buffering rectified DC voltages, including power supplies (UPS), variable frequency drives, wind power converters, photovoltaic inverters, traction drives and more. It is a highly matured product with decades of history and millions of pieces in usage. The continuous technology advancements of electrolytic capacitors in miniaturization, cost reduction and improved reliability contributed to the phenomenal innovations in the power conversion industries.

Construction of Electrolytic Capacitors

An aluminum electrolytic capacitor, or (e-cap), is a capacitor whose anode (+) consists of pure aluminum foil with an etched surface, covered with a uniformly, very thin barrier layer of insulating aluminum oxide, which operates as a dielectric. The electrolyte, which covers the rough surface of the oxide layer, operates as the second electrode, the cathode (-). The electrolytic capacitors used in the SINAMICS PERFECT HARMONY GH180 drives are non-solid electrolyte type capacitors; they are inexpensive and available in the widest range of sizes, capacitance (from 0.1 F up to 2,700,000 F) and rated voltage values (from 4V up to 630V). Figure 1 shows the typical construction of an aluminum electrolytic capacitor.

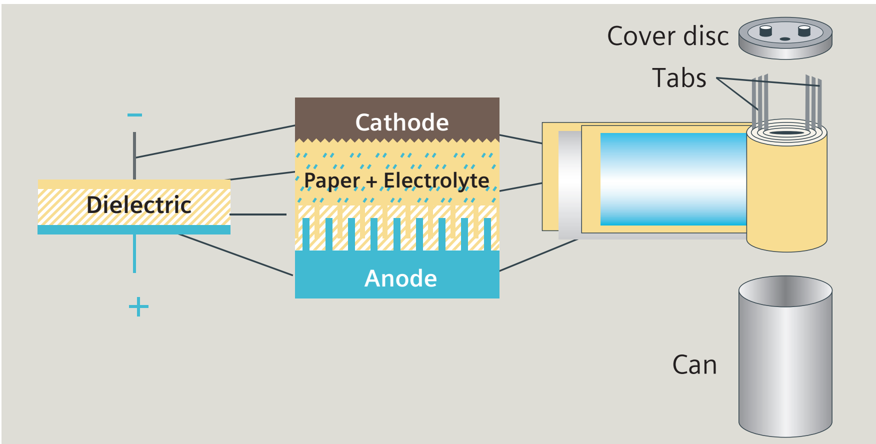

Figure 1: Construction of electrolytic capacitor [1]

Equivalent circuit and ESR

The electrical characteristics of capacitors are harmonized by the international generic specification IEC 60384-1. In this standard, the electrical characteristics of capacitors are described by an idealized seriesequivalent circuit with electrical components that model all ohmic losses, capacitive and inductive parameters of an electrolytic capacitor:

- C, the capacitance of the capacitor,
- R_{ESR}, the equivalent series resistance, which summarizes all ohmic losses of the capacitor, usually abbreviated as "ESR".
- L_{ESL}, the equivalent series inductance, which is the effective self-inductance of the capacitor, usually abbreviated as "ESL".
- $R_{leakage}$, the resistance that represents the leakage current

Equivalent Series Resistance (ESR) of an electrolytic capacitor is the resistance from the electrode foils, the electrolyte, the leads and each connection. This parameter is critical in the manufacturing of an electrolytic capacitor. Manufacturers control the material, design and assembly process to achieve a lower ESR.

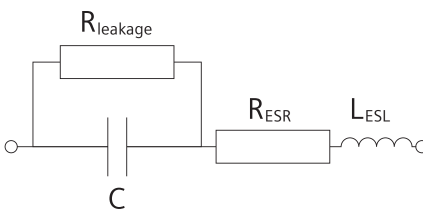

Figure 2: Equivalent Circuit of an electrolytic capacitor

Failure Modes of Electrolytic Capacitors

The failure modes of electrolytic capacitors can be classified in two categories: catastrophic failures and degradation failures.

Catastrophic failure is a failure mode which destroys the performance of the capacitor. Short circuit and open circuit are examples of this failure mode. This kind of failure usually occurs due to quality problems in production or mistakes made in capacitor application as the root cause. For example, burrs on the edge of aluminum foil or existence of small metal partials may cause a short circuit between electrodes. This type of failure must be controlled by the quality management process in manufacturing. An example of a mishandled application would be running a capacitor overvoltage, which may cause a short circuit between electrodes of the capacitor. This type of failure can usually be addressed through proper design of the equipment and provision of protection features in the equipment. Catastrophic failure is not related to the lifetime of the electrolytic capacitors and therefore, not the focus of this paper.

Degradation failures, also called wear-out failures, are caused by the gradual deterioration of the capacitor's electrical parameters. In the case of a degradation failure, the capacitor shows a decrease in its capacitance and an increase in the Equivalent Series Resistance (ESR). This failure is primarily due to the degradation of the electrolyte leading to a loss in conductivity, and the gradual evaporation of the electrolyte with usage. Other causes may include deterioration of aluminum foils or oxide layers [3].

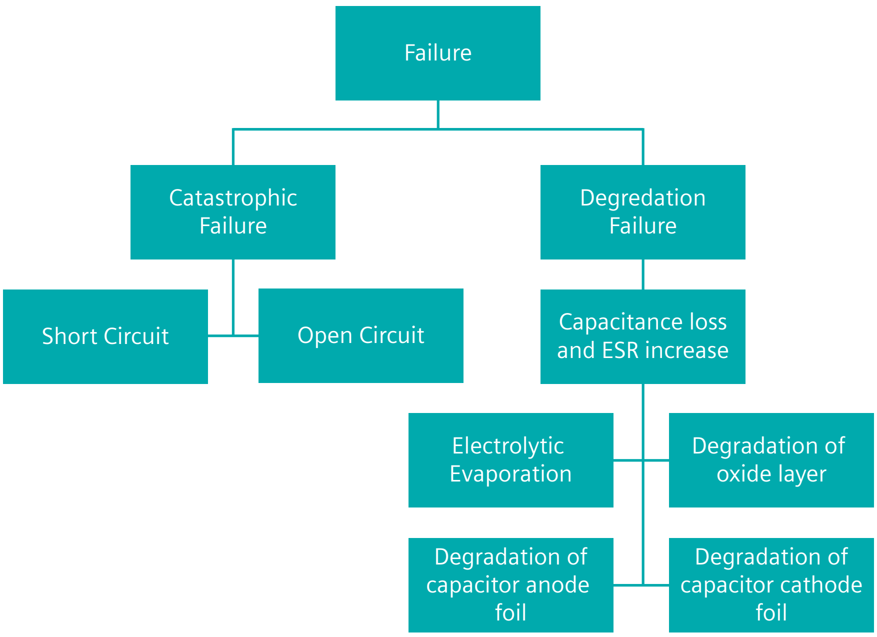

Figure 3: Failure mode of electrolytic capacitor [2]

A degradation failure can be judged by the loss of capacitance from initial value. The criteria for judging failures vary by application and design factors. An electrolytic capacitor is considered to be completely degraded when 30% of its initial capacitance is lost or its ESR reaches 300% of the initial value.

The wear-out of an electrolytic capacitor is a permanent, cumulative and irreversible process. The initial increase of ESR has limited impact on the performance of the capacitor. But when the increasing ESR accumulates to a certain high level, the ohmic losses becomes big enough to lead to further increase of the internal temperature of the capacitor; in turn accelerating the evaporation of electrolyte and further increasing the ESR. This cycle can lead to an exponential increase of the ESR (see Figure 4) and a fast wear-out failure of the capacitor when it approaches the end of its life.

The life time of capacitor is defined as the time that the degradation failure happens for a capacitor. Figure 5 is a failure analysis for a typical electrolytic capacitor, which shows a consistency in how often these degradation failures happen. The figure also shows a fast increase of the failure rates as the capacitor's end of life approaches.

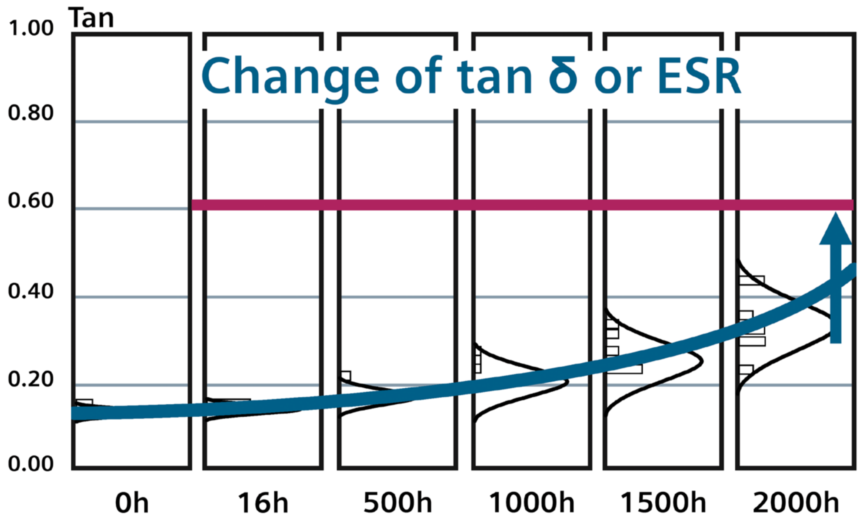

Figure 4: Change of ESR

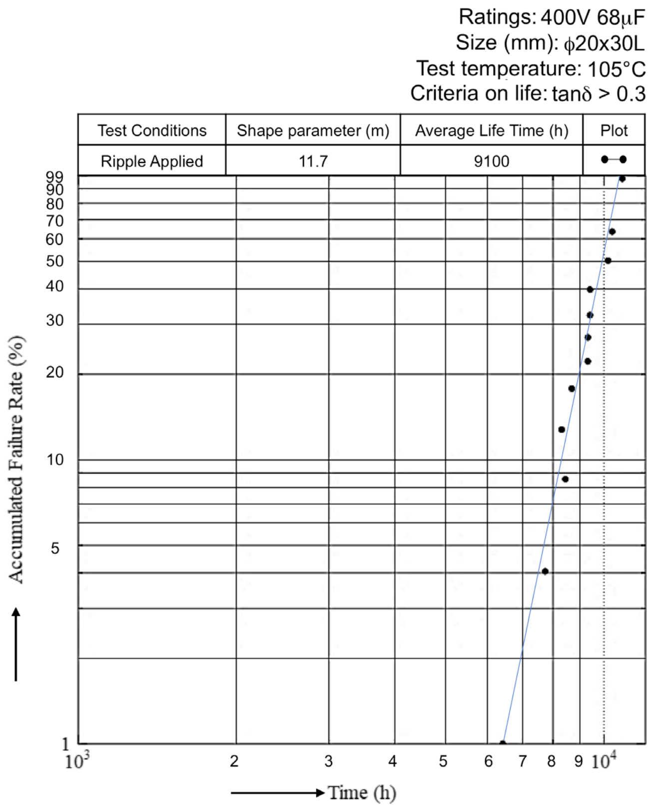

Figure 5: Failure Analysis by Weibull Probability Paper [4]

Lifetime of Electrolytic Capacitors

Factors Impacting Capacitor Life

Capacitor manufacturers design each type of capacitors to specific operating lifetime expectancy, however the lifetime of the same capacitor vary significantly based on the electrical applications. It is also very much dependent on the environmental and electrical factors in which it is designed to operate.

The design lifetime of capacitors in a product application is evaluated by accelerated life tests. The acceleration tests contain three factors shown by the following equation:

$L_X = L_0 * K_T * K_V * K_R$ [5]

Where:

L_X = Resulting lifetime
L_0 = Lifetime at nominal ripple and upper category temperature
K_T = Temperature factor
K_V = Voltage factor
K_R = Ripple current factor

Better product design like that of the SINAMICS Perfect Harmony GH180, improves these factors can also improve the resulting lifetime of the electrolyticcapacitors being manufactured.

Effects of Temperature on Life

Temperature is the most critical aspect to the life of electrolytic capacitors. This is because increased temperature accelerates the chemical reaction rates within the capacitor and leads to accelerated electrolyte evaporation, which is the primary process of degradation failure. Usually a 10°C rise in temperature doubles the chemical reaction rate, therefore halves the life expectancy of the capacitor, as shown in figure 6.

Effects of Ripple Current on Life

When ripple current flows through the capacitor, heat is generated by the power dissipated in the capacitor and causes temperature rise. The approximate heat (power loss) generated by ripple current can be calculated as follows:

$W \sim= I_R^2 * R_{ESR}$

Where:

I_R^2 = Ripple current
R_{ESR} = Equivalent Series Resistance

Assuming all other things being equal (cooling condition, can size and ESR), temperature rise on the capacitor due to ripple current are proportional to the power of the ripple current. Figure 7 shows an example of the lifetime expectancy under different ripple current.

Effects of Voltage on Life

The operating voltage affects the capacitor life by a factor as the power of the ratio of operating voltage to the rated voltage of the capacitor. By either selecting higher rated voltage capacitor or lowering operating voltage the capacitor life can be extended to some extent, but this effect is normally less than the effect from temperature and ripple current.

In addition, applying excessive voltages on a capacitor will rapidly increase its leakage current, causing internal overheating, gas generation or actual dielectric break down. Operation of the pressure relief vent, can swelling, or deformation are often seen in overvoltage cases.

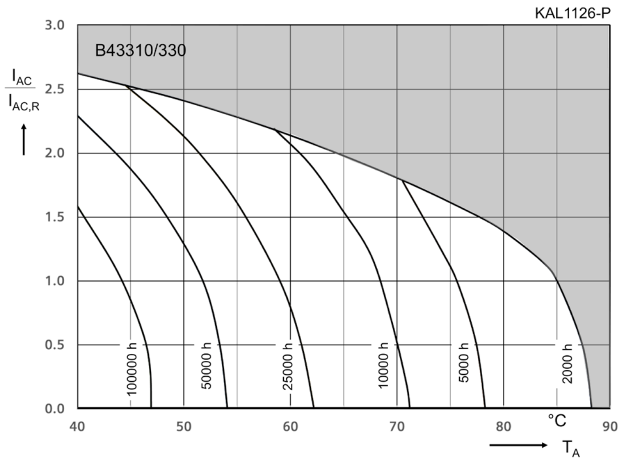

Figure 6: Temperature effect [6]

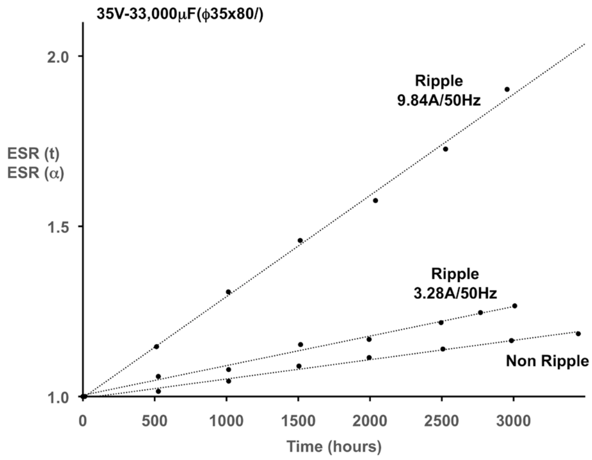

Figure 7: Ripple current effect [7]

Electrolytic Capacitor Design in SINAMICS PERFECT HARMONY GH180 Drives

With over 20-years' experience in the design and manufacturing of SINAMICS PERFECT HARMONY GH180 drives, Siemens has optimized the design and manufacturing process to extend the capacitor life while considering the effects from all above factors.

Capacitor Selection
The capacitors used in the SINAMICS PERFECT HARMONY drives are all from qualified suppliers. The capacitors Siemens utilizes are the longest-useful-life, lowest ESR and higher voltage capacitors in the suppliers' portfolio.

Cooling of Capacitors
In the SINAMICS PERFECT HARMONY drives manufactured after the year 2007, the cooling air (ambient air) approaches the capacitors when coming into the cell, cools the capacitors first and then cools the power electronics (figure 9). This sequence is opposite to the cooling sequence in the older generations of the cell design and all competitive clone designs of the SINAMICS PERFECT HARMONY drives, (figure 10), in which the cooling air was heated up by the power electronics before approaching the capacitors. Because ambient temperature is the primary driver of capacitor life (double life for every 10°C decrease), Siemens has developed a superior cell design that significantly improves the life expectancy of the capacitors.

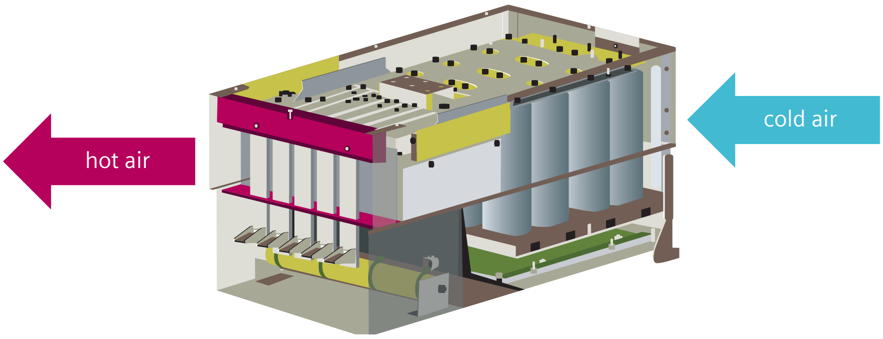

Figure 9: SINAMICS PERFECT HARMONY power cell air flow

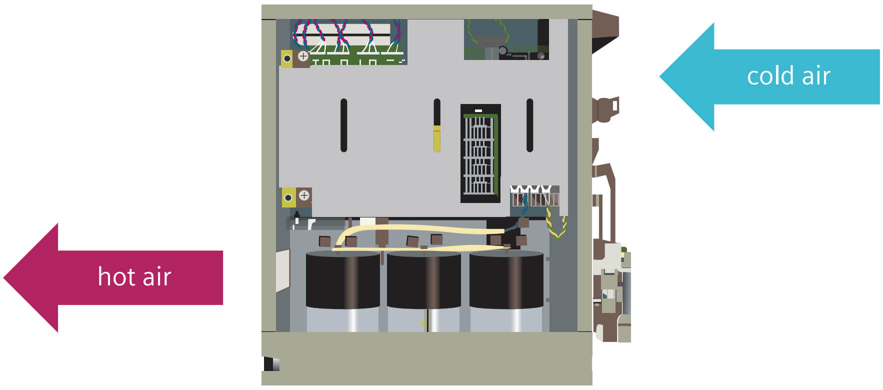

Figure 10: SINAMICS PERFECT HARMONY clone drive power cell air flow

Ripple Current
Ripple current is caused by the variable frequency drive's topology and the high frequency when switching from the PWM control. Ripple current is inevitable and the job of the capacitors as the DC link filter is to smooth this ripple current.

To reduce the ripple current on each capacitor, the power cell needs to have more capacitance (i.e. a bigger filter) built in. For example, within the SINAMICS PERFECT HARMONY cells, there are stringent rules to sufficiently size capacitance in the cell design. However, many drive manufacturers have 1/3 less capacitance in their power cells which will lead to a shorter lifetime of their capacitors.

A lower ESR of the capacitor can help reduce the power loss caused by ripple current, this is the reason Siemens always selects low-ESR capacitors.

Operating Voltage

Electrolytic capacitors are sensitive to over voltage, in the GH180 GenIV and GenV cells, 450V rated capacitors are used while the actual applied nominal voltage is only 350V. In contrast, many competitors use cheaper 400V rated capacitors in their power cells.

Within Siemens power cells, the capacitor bank has a serial connection of parallel capacitors (figure 11) to achieve the required voltage and capacitance. Precise voltage sharing among the capacitors is important to ensure each capacitor realizes the same voltage and operates well under its rated voltage. The Siemens cell design has voltage sharing resistors and low impedance bus work in the cell to assure the voltage sharing on both AC and DC components.

Furthermore, in production, manufacturers should ensure the capacitors used in one cell are from the same batch of the same supplier, and first-in, first-out (FIFO) material is followed to ensure the uniformity of the capacitors' electrical characteristics.

Lastly, protection schemes should be built into the cells to monitor not only DC bus voltage but also voltages on the capacitor banks. This would help to protect the capacitors in case of abnormal situations, e.g. failure from other components or motor side voltage excursions.

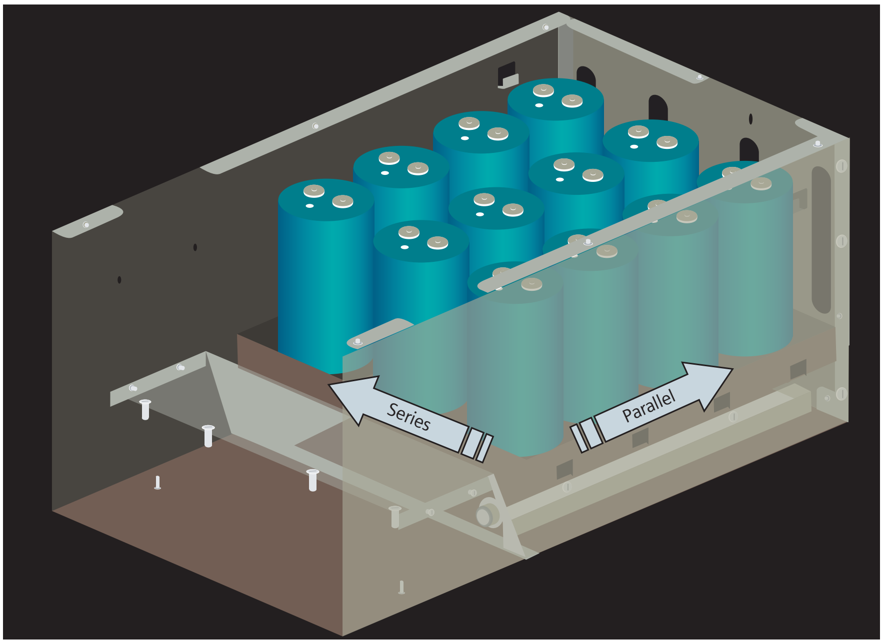

Figure 11: Connection of DC capacitors in Siemens cells

Design Life of Capacitors in GH180 Power Cells

At Siemens, the design life of SINAMICS PERFECT HARMONY GH180 power cells are documented in the cell manual (table 1). Power cells are rigorously tested based on the corner conditions of the drive specification and calculated with the capacitor life model from conservative initial values:

- Testing ambient temperate = 40°C
- Testing current = rated current
- Overload = 110%
- Testing air flow = rated air flow
- Operating duty = 24*365 hrs

The table shows SINAMICS PERFECT HARMONY power cells have >15 years design life expectancy under rated input voltage thanks to the unique design of the power cell.

Parameters Data	Cells					
Rated Output Current Rating[1]	40Arms	70Arms	100Arms	140Arms	200Arms	260Arms
110% 1min/10min (CL-1)[2]	40Arms	70Arms	100Arms	140Arms	200Arms	260Arms
150% 1min/10min (CL-2)[3]	40Arms	70Arms	100Arms	130Arms	200Arms	260Arms
Typical Operational Life, years, 10% high line input voltage[10]	12.87	15.65	16.61	15.65	13.3	18

Table 1: Design life of SINAMICS PERFECT HARMONY GH180 power cells

Service Life

Factors Impacting Service Life
Due to varying installation factors including different environmental, operating and maintenance conditions of the drive, the service life of capacitors in a variable frequency drive can vary significantly and may be far extended from the design lifetime.

The first factor to take into consideration is ambient temperature. A drive operating at 30°C will have approximately double the life expectancy of its power cell versus the design life. In the instance of a Siemens SINAMICS PERFECT HARMONY drive, a 15 year life is easily achievable for SINAMICS Perfect Harmony systems at normal ambient conditions. In industrial level equipment rooms with HVAC or heat exchanging cooling systems, cell capacitors may well last beyond 20 years under good condition and maintenance. On the contrary, if air-filters were blocked during operation due to lack of maintenance, this could lead to a poorer cooling situation of the power cell, and the real service lifetime of the capacitors will be shortened.

The second factor to consider is the oversizing of equipment. In many applications a VFD is operated at <70% of its rated current due to the 'stacking' of oversized equipment due to safety factors. Reduced operation is even true on most energy saving applications such as pumps / fans / compressors since this is where energy saving comes from. In such cases, the ripple current and temperature rise on the cells are significantly less than the rated condition and the capacitor lifetime is extended.

Finally, capacitor wearing is cumulative. Every hour the capacitor is running at full rated voltage and temperature, it uses one hour of the total design life. For example, the SINAMICS PERFECT HARMONY GH180 drive is designed for continuous operation, so if the drive is operating at 8 hours per day, the drive is only utilizing 1/3 of the capicitor for that day as it was intended to run for a full 24-hour period. Therefore, the capicitor could last up to 3 times longer.

Under good environmental conditions, regular maintenance and light duty applications, the capacitor may last significantly longer than the design life. A good example is Siemens very first generation of PERFECT HARMONY drives, some of which are over 20 years old and are still running with their original cells.

Field Data
Siemens has been manufacturing SINAMICS PERFECT HARMONY drives for over 20 years and has more than 870 drives installed globally that are more than 15 years old. From the first installation of a SINAMICS Perfect Harmony Drive, Siemens has captured data on capacitor wear-out failures. They are extremely rare during the initial 8~10 years of the drive's life, and only in certain heavy duty applications may they start to appear after 12 years.

Conclusion

In conclusion:

1. The design life of capacitors in Siemens' SINAMICS Perfect Harmony drives is 13 to 18 years (see Table 1).
2. Real service life of the capacitors is not a constant number; it is driven by multiple factors including operating temperature, maintenance conditions, load cycles and operating duty. In light duty applications, the capacitor life can be extended well beyond its standard design life.
3. In critical applications it is recommended to inspect the capacitor as part of a regular maintenance schedule when it approaches the end of its life since risk of failure may start to increase. This is to evaluate the condition of the capacitor, detect the early signs of degradation, and perform necessary preventive maintenance.

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